Stability slopes study of dams of Necaxa Hidroelectric System

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ABSTRACT
In order to evaluate the structural behaviour and to obtain the safety factors of dams of the Necaxa hydroelectric system was carried out an analysis of slope stability using numerical models. The field work consisted of topography and bathymetry to characterize geometrically the dams. To obtain the mechanical properties of the material dams, geotechnical exploration was performed through permeability tests, standard penetration tests and recovery of samples and one-dimensional consolidation tests, triaxial tests and index test. Once constructed the models were applied methods of analysis and limit equilibrium method for pseudostatic seismic analysis. To review the effect of piping was carried out chemical analysis of water in the reservoirs. The results led to recommendations on the structural conditions of dams.

RÉSUMÉN
Con el fin de evaluar el comportamiento estructural y obtener los factores de seguridad de las presas que integran el S.H. de Necaxa se llevo a cabo un análisis de estabilidad de taludes utilizando modelos numéricos. Los trabajos de campo consistieron en levantamiento topográfico y batimétrico para caracterizar geométricamente la cortina. Para obtener las propiedades mecánicas de los materiales que conforman los diques se realizó una exploración geotécnica, a través de pruebas de permeabilidad, pruebas de penetración estándar y recuperación de muestras, así como pruebas de consolidación unidimensional, ensayes triaxiales y pruebas índice. Una vez construidos los modelos se aplicaron métodos de análisis de equilibrio límite y un método pseudoestático para el análisis sísmico. Para revisar el efecto de tubificación se llevó a cabo análisis químico del agua de los embalses y vertedores de filtración. Los resultados permitieron dar recomendaciones sobre las condiciones estructurales de las presas.

1 INTRODUCTION

Necaxa Hydroelectric System (NHS) has been a major civil engineering construction to generate and supply electricity to the central region of Mexico. This system was inaugurated in 1903 and has successfully operated for a period longer than its expected lifetime. The system consists of five hydraulic fill dams, canals, tunnels and conduction pipelines.

Despite its adequate performance, the reliability of several components - such as dams, tunnels and pipes under pressure - has decreased due to its long operating life and the changing weather conditions. Such is the case of “Tenango” and “La Laguna” dams. The first experienced in 1968 a fault piping (Marsal and Resendiz, 1975), and it was necessary to repair a section of its curtain. In 1999, the reservoir levels reached one of its highest elevations. At that time movements were observed in Tenango dam, which indicated a potential slope failure. As an emergency measure, berms were built to stabilize the slopes.

In order to prevent future problems in these dams, the extingued Light and Power Company of Centre asked the Electrical Research Institute to review the stability of dams in NHS in their current condition. In order to perform the stability analysis of the dams’ curtains, it was necessary to determine mechanical properties and conditions of permeability of their materials. Taking into account the configuration of each dam, a program of exploratory drilling and sampling was conducted as well as planimetric and altimetric surveying activities on the curtain and bathymetry work on the flooded embankments. The determination of cross sections geometries of the curtains was essential to develop analytical models of stability in areas considered as critical.

NHS is located near Huauchinango city, in the limits of Puebla and Hidalgo states in Mexico (Figure 1). The regional geological framework of the geographical area corresponds to the southern end of the geological and geomorphological province of the “Sierra Madre Oriental”. Nuevo Necaxa area, between Xicotepec and Huauchinango, in the state of Puebla is a narrow 50 km wide and 100 km long, oriented NNW and runs to NW through the state of Hidalgo.

2 TOPOGRAPHY AND BATHYMETRY FOR DAMS GEOMETRIC CONFIGURATIONS.

Topographic surveys were conducted in each of the dams with a total station having a linear tolerance of 1:10,000 and 5 seconds accuracy. It was used to support open polygonal stations located along the crown of the dam. Over the crown and the upstream slope of the dams are landmarks, whose elevations are referenced to the existing level bank, which in all cases is located at the top of the outlet tower. The profiles were built with a direct placement using the method of differential levelling. Three-dimensional coordinates were processed to represent schematically the configuration of the ground; triangulations were made between points and ground level curves were obtained.

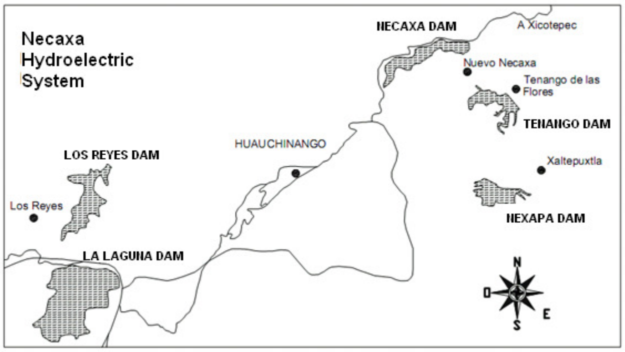

Figure 1. Location of NHS dams

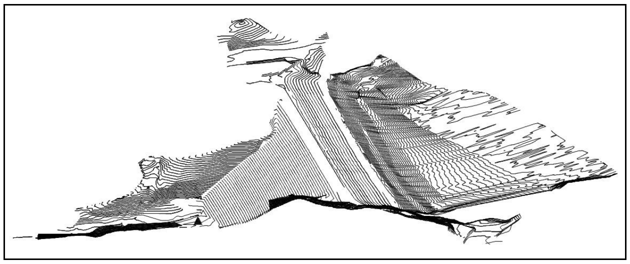

Figure 2. Topography and bathymetry for Necaxa dam

Bathymetric studies using echo-sound were made in order to establish the geometrical configuration of submerged slopes of the dams. The main purpose of a bathymetric survey was to obtain the depth of water, the angle of the slopes. The bathymetric studies were performed along a series of lines on the curtains. The sweeps were done at a moderate speed to ensure the accuracy of the GPS readings. The information was processed to obtain the contour of the bottom of the basin and later linked with the information of the topographical survey of the area and to determine the current topographic settings of each of the dams. Once this was completed, cross-sections of each dam were obtained and used to generate the analysis models, Figure 2.

3 PHYSICAL AND GEOMECHANICAL CHARACTERIZATION OF DAMS MATERIALS.

3.1 Structure and Composition of the Dam

Tenango dam is composed, in its maximum section, of three materials: Upstream are placed heavy earth materials, with a maximum triangular section to 1338 masl. The rockfill is placed downstream in a triangular section with maximum elevation at 1347 masl. Among these materials is deposited hydraulic filling of fine grain size, with maximum elevation on the crest of 1353 masl. At the base of the curtain, along its axis and embedded in the foundation rock (basalt) there is one concrete key trench with variable depth (Fig 3).

Necaxa Dam is also composed of three materials (Fig. 4). Downstream is a rockfill of triangular section with a maximum height of 1333 masl. Upstream are placed heavy earth materials, with a maximum triangular section to 1320 masl. Among these materials is deposited hydraulic filling of fine grain size, with maximum elevation on the crest of 1344 masl. At the base of the curtain, along its axis and embedded in the foundation rock (basalt) there is one concrete key trench with variable depth, with a maximum of 15 m, and four trenches run parallel to the concrete key trench; two are located upstream and two downstream.

Nexapa dam is also composed of three materials: Upstream are located the heavy materials, with a maximum elevation or 1347.5 masl. The rockfill is located downstream in a triangular section with elevation of 1348 masl. Between both materials there are hydraulic fills deposited of fine grain size. At the base of the curtain, along its axis and embedded in the foundation rock (basalt) there is one concrete key trench with variable depth.

La Laguna Dam, (Fig 5), is of earth core and concrete wall type. In the central part of the core, the concrete wall is one meter thick, and penetrates the dam foundation. In the area where failure occurred in the year of 1969, a cement-bentonite wall with a maximum depth of 26 m was built. The body of the dam is composed for three different types of earth materials. The upstream slope has impermeable material with very soft consistency (clay-sand). The downstream slope is composed of coarse materials (gravel and boulders) in a silt-clay matrix; they are very permeable. The core was made of gravel hand packed in fine material, with an intermediate degree of permeability.

Los Reyes dam (Fig 6) consists of an upstream cofferdam and diaphragm of waterproof timber (built in a first stage) and a backup of earth and rockfill downstream. Between the two previous materials there is a space with trapezoidal section filled with material hydraulically deposited. The crest of the curtain was built with layers of clay compacted by hand. At the base of the curtain, along its axis and embedded in the foundation soil there is one concrete key trench with variable depth, with a maximum of 7 m. The downstream slope is composed of coarse material (gravel, boulders and blocks), packaged in silty-clay with low plasticity.

3.2 Geomechanical characterization

In the exploration phase, the technique of standard penetration test was used to obtain disturbed samples, which were tested to obtain index parameters. In addition, undisturbed samples were obtained using Shelby tube (thin wall) in soft soil and NQXL barrel on rock.

On these samples CU, UU and consolidation tests were performed to determine shear strength and consolidation coefficients. The permeability of different materials in the core of the curtain was determined through Lefranc Type field testing.

To obtain material properties of the core of the curtain of the Tenango dam, 10 boreholes were made on the crest of the dam and 6 on the slopes to measure the thickness of rockfill that covers the finest soil materials. During the drilling of boreholes, drilling mud was lost at different depths. The most outstanding is the borehole on the landmark 2 located on the crest, where the mud was lost to 2.4 m depth, probably due to cracks in the clay or piping.

In the boreholes close to 25-26 y 35 landmarks drilling mud was also lost. The extracted materials were identified as CH and CL. The percentage of fines that passed the No. 200 mesh was generally greater than 90% in almost all samples taken from the hydraulic fill. As for the rockfill, a friction angle of 36° was considered (Marsal, 1975), taking into account that the material was placed to turn and has compacted during its operation period getting more stability. The critical sections of the dam were defined based on the stratigraphy results of the exploratory drilling. Table 1 and Figure 7 present the mechanical properties and permeability of critical sections.

In the curtain of Necaxa dam were drilled 6 geotechnical boreholes, four on the crest (66, 68 and two 45 m deep) and two on the downstream slope. The slopes borings were aligned with crest borings, to obtain cross sections. In two boreholes the basement rock was reached and deepened further 4 and 5 m, respectively. In some parts of the curtain, during the standard penetration test, the bars were driven into the material by its own weight, which indicates a very low resistance. The minor strengths were between 5 and 25 m of depth and represent a potential area of failure by sliding surfaces, which was considered in the stability analysis. It was observed that materials that include boulers and gravel do not form well defined layers. Rather they were erratically deposited forming regions or areas with resistance due to friction and cohesion and higher permeability, where significant seepages may occur. On the downstream face, deformations were observed altering the flat geometry of the slope. It was not possible to measure the age or the speed of these deformations to determine whether they are growing or stable. The installation of inclinometers is recommended. Table 2 and Figure 8 present a summary of the properties of the Necaxa dam.

To obtain the material properties of the core of the Nexapa dam, three boreholes were made on the crest: 43, 50 and 60 m deep, respectively. To measure the thickness of rockfill that covers the fine earth materials four boreholes were drilled in the slopes of the curtain. Permeability tests (Lefranc type) were conducted at different depths in the body of the curtain. In the exploration and sampling works, there was not loss of mud, so it can be seen that the curtain has no cracks or piping. Limestone rock makes the foundation of the dam. Its impermeable core could be considered homogeneous according to soil type, but not if the number of blows of SPT and the permeability coefficient are considered. For this reason the critical section was analyzed with the stratigraphy shown in Table 3 and Figure 9. In some drilling, more than 25 blows in the SPT were needed, which is indicative of having a firm consistency.

At La Laguna Dam, 4 borings were made in the core (9, 17, 20 and 21 m deep) and 6 boreholes on the slopes of the curtain to detect the thickness of rockfill that covers the fine earth materials (15 m deep). Permeability tests were conducted at different depths, both on the material of the curtain as on the natural support soil. The materials found in the upstream slope, in general show a soft, low resistance, with a high degree of uniformity in the longitudinal direction. The core material shows a large variability in permeability and resistance. In the most superficial zone there is low permeability silty material, which is followed by very permeable boulers and gravel. The foundation of the curtain is made up of cracked basalt rock with signs of injections in some places and disturbed basalt of varying thickness, also reported by Marsal and Resendiz (1975). Table 5 and Figure 11 present a summary of the material properties of the La Laguna dam.

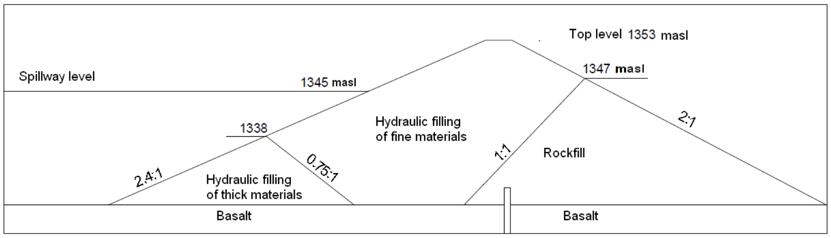

Figure 3. Maximum cross seccion of Tenango Dam

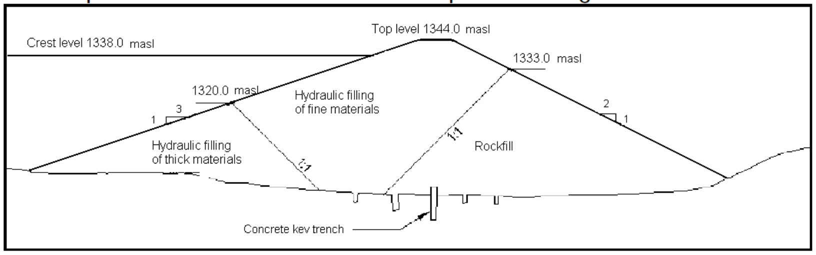

Figure 4 Maximum cross seccion of Necaxa Dam

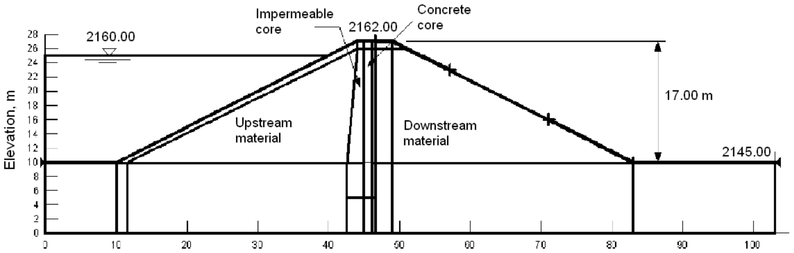

Figure 5 Maximum cross seccion of La Laguna Dam

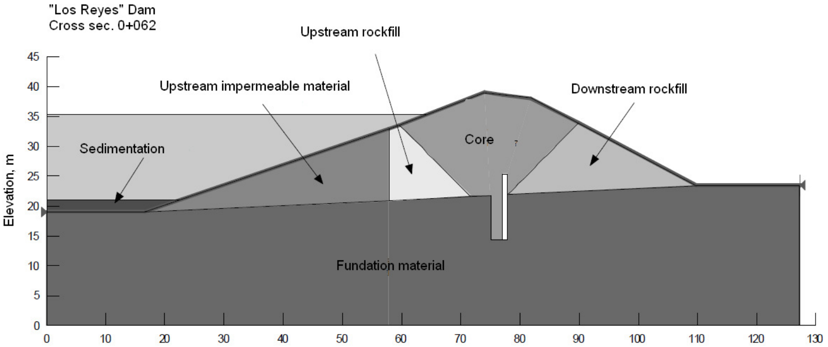

Figure 6 Maximum cross seccion of Los Reyes Dam

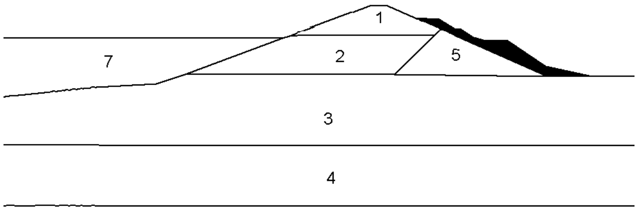

Figure 7. Critical cross section 1, Tenango dam (between landmarks 2 and 3)

Table 1. Material Properties in critical section 1, Tenango dam

Material	γ (kN/m^3)	UU Test c (kPa)	 ϕ (º)	CU Test c (kPa)	 ϕ (º)	 c' (kPa)	 ϕ' (º)	k (m/s)
1. Clay	16.0	36.0	0	28.4	15.5	17.6	22.29	1×10^{-8}
2. Ligth brown clay	16.0	36.0	0	28.4	15.5	17.6	22.29	1×10^{-7}
3. Disturbed tuff	19.0	65.7	0	28.4	15.5	17.6	22.29	1×10^{-7}
4. Basalt	-	-	-					-
5. Curtain rockfill	19.0	0.0	28.0					1×10^{-2}
6. Berm rockfill	19.0	0.0	35.5					1×10^{-2}
7. Water	9.8	-			-			-

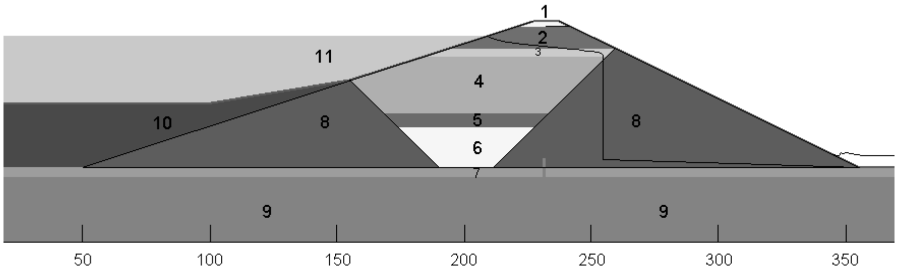

Figure 8. Critical section 3, Necaxa dam

Table 2. Material properties in critical section 3, Necaxa dam

Material	γ (kN/m^3)	UU test c(kPa)	ϕ (º)	CU test c (kPa)	ϕ (º)	c'(kPa)	ϕ '(º)	k (m/s)
1. Heterogeneous material	19.0	-	-	-	-	-	-	1.0×10^{-3}
2. Light brown clay	16.7	17	0	31.75	16.5	6.76	31.46	1.0×10^{-6}

3. Clay with boulders	17.0	17	0	31.75	16.5	6.76	31.46	$4.4X10^{-3}$
4. Clay	17.65	17	0	31.75	16.5	6.76	31.46	$1.0X10^{-7}$
5. Sility with sand and gravels	17.5	17	0	31.75	16.5	6.76	31.46	$7.5X10^{-4}$
6. Sandy clay	17.0	17	0	31.75	16.5	6.76	31.46	$1.0X10^{-5}$
7. Sand	19	0	38	-	-	-	-	$1.0X10^{-6}$
8. Rockfill	19	0	36	-	-	-	-	$1.0X10^{-1}$
9. Basalt	-	-	-	-	-	-	-	-
10.Reservoir sediment	14.0	1.0	0	-	-	-	-	$1.0X10^{-7}$
11.Water	9.8	-	-	-	-	-	-	-

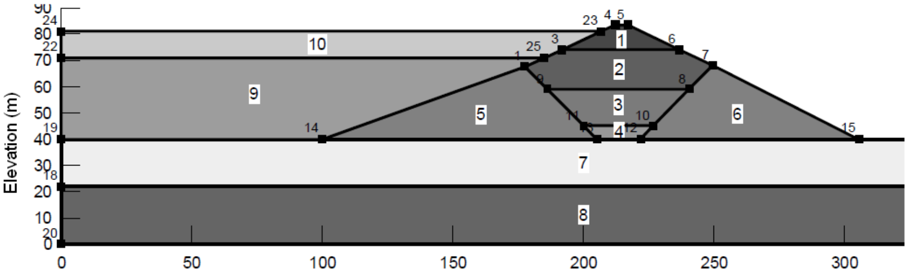

Figure 9. Critical section 1, Nexapa dam

Table 3. Material properties in critical section 1, Nexapa dam.

Material	γ(kN/m^3)	c_u (kPa)	Φ (º)	*k* (m/s)
1. Sility clay	13.0	21.5	--	10^{-9}
2. Sility clay	14.5	35.75	--	$1.5X10^{-7}$
3. Sility clay	18.0	110.0	--	$1.8X10^{-6}$
4. Arcilla limosa	17.0	75.0	--	$3.7X10^{-7}$
5 y 6.Rockfill	20.0	--	35.0	10^{-1}
7. Limestone	21.0	5000	--	10^{-7}
8. Basalt	26.0	--	40.0	10^{-10}
9. Reservoir sediments	14.0	--	--	10^{-4}
10. Waters	9.8 (10.8)	--	--	--

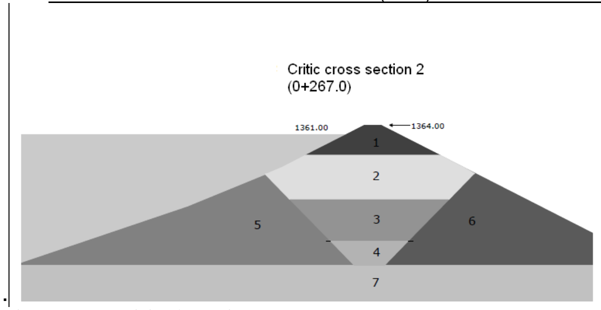

Figure 10. Critical section 2, Los Reyes Dam

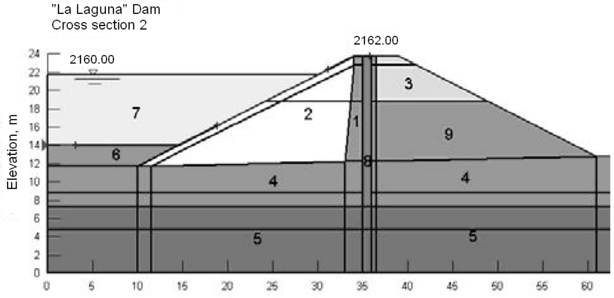

Figure 11.Critical section 2, La Laguna Dam

Tabla 4 Strength properties obtained in CU test

		Friction angle		Cohesion	
Borehole	Depth (m)	Total stress ϕ (º)	Effective stress ϕ' (º)	Total stress c (kPa)	Effectives stress c' (kPa)
SM-2	4.0-4.60	2.03	4.35	32.73	30.0
SM-4	9.4-10.0	16.73	25.68	7.84	3.43

Tabla 5. Material properties in critical section 2, La Laguna dam.

Material	γ (kN/m^3)	UU test c (kPa)	ϕ (º)	CU test c (kPa)	ϕ (º)	c' (kPa)	ϕ ' (º)	*k* (m/s)
1. Impervious core	15.1	-	-	32.7	2.0	30.1	4.35	$8.1 X10^{-6}$
2. Upstream material	15.1	-	-	32.7	2.0	30.1	4.35	$9.6 X10^{-8}$
3. Downstream material	13.4	-	-	32.7	2.0	30.1	4.35	$1.0 X10^{-8}$
4. Disturbed basalt	16.0	-	-	7.84	16.73	3.43	25.68	$9.9 X10^{-8}$
5. Boulders and blocks	-	-	-	-	-	-	-	$1.0 X10^{-4}$
6. Reservoir sediments	12.75	0	0	0	0	0	0	-
7. Water	9.81	-	-	-	-	-	-	-
8. Impervious wall	22.0	-	-	980	-	-	-	$1.0 X10^{-10}$
9. Downstream material	15.1	-	-	7.84	16.73	3.43	25.68	$1.0 X10^{-8}$

The materials found in all the drillings on in the core of the curtain of Los Reyes dam have a heterogeneous composition, ranging from clay particles to sand and gravel. Therefore, an average value of resistance may be considered. The downstream slope is composed of plastic material overlying boulers and rocks packaged in fine materials. In this section of the dam, the Le Franc test showed high permeability.

One of the critical sections for analysis was selected where the body of the dam is founded on a natural slope which contains fine soil (silty-clay).

4 STABILITY ANALYSIS

4.1 Methodology

The critical sections for stability analysis were selected based on the reports of geotechnical explorations and the geometry of the dams obtained in topography and bathymetric studies. For each dam, at least two critical sections for analysis were defined. However, this work only reports the results of the section with the lowest safety factors. Critical sections were labeled using both physical references and distances from one end of the crest of the dam.

The stability of the dams was evaluated by deterministic methods, by means of safety factor (SF) defined as the ratio between resistant and acting forces. The FS was obtained using a general limit equilibrium analysis in 2D. The most critical failure mechanism considered was circular slip surface. Pore pressure used in the analysis was obtained from water flow condition in 2D. Horizontal and vertical seismic forces equivalent to a fraction of the weight of the soil volume considered were used in the numerical model. The analysis conditions were: reservoir empty, steady flow, rapid drawdown and earthquake. Commercial software was used to perform the analysis: Modified Bishop and Spencer methods. Hydrodynamic pressure and flow of water through dam and foundation were also modeled. Hydrodynamic pressure was calculated as described by the Manual de Diseño de Obras Civiles (CFE, 1993).

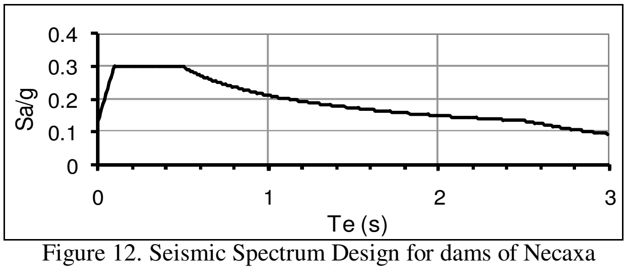

Figure 12. Seismic Spectrum Design for dams of Necaxa hydroelectric System

The seismic stability analysis was made following the recommendations of United States Corp of Engineers. According to Hynes-Griffin and Franklin (1984) the pseudostatic seismic coefficient can be used to assess the stability of a dam when: a) the material of the dam is not susceptible to liquefaction, b) small deformations of the dam does not represents a risk or a significant loss of strength of the materials, and c) the dam is not subject to earthquakes of magnitude 8 or greater. In this case, if a seismic coefficient equal to half of rock base acceleration is used and the pseudostatic analysis results in a SF greater than 1.0, the dam will not exceed the deformation limits of tolerance.

The applicability of the method is based on results of triaxial tests on material of the dams that show a ductile behavior, without sudden loss of strength. Also, the materials of the dams are not susceptible to liquefaction. In regard to the likely occurrence of earthquakes of great magnitude, Pérez Rocha (2006) determined the design spectrum for the group of dams considering a continuous variation of seismic hazard in Mexican territory. The spectrum does not have reduction factors unrelated to seismic hazard. Acceleration in the basement rock of the design spectrum was a0= 0.13g. Therefore, the seismic coefficient used was c = 0.065.

In the pseudostatic method the seismic forces were represented in terms of pseudostatic accelerations ah and av, and the associated inertial forces Fh y Fv.

$$F_h=a_h\, W/g = k_h\, W \quad [1]$$

$$F_v=a_v\, W/g = k_v\, W \quad [2]$$

Where: g = gravity acceleration; kh, kv = horizontal and vertical seismic coefficients; W= weight of sliding volume.

The forces Fh and Fv, the resistant forces and the weight of sliding volume form the equation of equilibrium of forces and moments. The result is the SF.

Additionally, it was employed Newmark-type sliding block analysis for computation of permanent deformations due to earthquake.

The minimum acceptable SF were those recommended by Reséndiz et al (1975): for established flow SF ≥ 1.5; rapid drawdown FS ≥ 1.3. For seismic condition FS ≥ 1 computed with pseudostatic method and in accordance with the recommendations of Hynes-Griffin y Franklin (1984).

4.2 Results

Figures 13 to 17 illustrate the stability analysis performed for the five dams. Table 6 contains the summary of the safety factors found for the different conditions of analysis. The seismic analyses performed with the Newmark-type sliding block method showed that the yielding acceleration was greater than the maximum spectral acceleration for all dams. So, the dams will not suffer permanent deformation.

Table 6. Minimum Safety Factors for Critical Sections

Method/Condition	Steady Flow	Draw-down	Seismic
Tenango Dam, Critical Section # 3			
BISHOP	1.464	1.697	1.49
SPENCER	1.463	1.692	1.44
Necaxa Dam, Critical Section # 2			

BISHOP	1.538	2.1	1.26
SPENCER	1.542	2.12	1.26
La Laguna Dam, Critical Section # 3			
BISHOP	1.733	1.327	1.51
SPENCER	1.766	1.367	1.525
Los Reyes Dam, Critical Section # 2			
BISHOP	1.885	1.449	1.527
SPENCER	1.881	1.449	1.527
Nexapa Dam, Critical Section # 1			
BISHOP	1.216	1.303	1.026
SPENCER	1.216	1.275	1.026

Safety factors of the three sections analyzed for Tenango dam are greater than the minimum recommended ones (USACE, 2003). Only in the downstream slope safety factors were slightly lower than those recommended, however, these granular materials are stable if the angle of inclination of the slope is greater than the angle of resistance. In addition, the slip surfaces associated with these SF occur on the surface of the slope, containing a small amount of material and do not represent a condition of instability of the slope. The slip surfaces that penetrated deeper and other critical sections had SF greater than 1.5 for the same condition. Using the criteria Hynes-Griffin and Franklin, the 3 sections have pseudostatic safety factor greater than one, therefore, they will not suffer large deformations that could threat the safety of the dam. However, the loss of drilling mud during the geotechnical exploration indicated the existence of cavities and they could facilitate the development of slip surfaces.

For Necaxa dam, the SF for steady flow condition is greater than the minimum recommended by Reséndiz (1975) and is considered satisfactory for the stability of the dam. The seismic coefficient c = 0.065, equal to half the peak ground acceleration produces a SF = 1.26, according to the Newmark method, so the dam is not expected to become permanently deformed.

For steady flow condition, Los Reyes dam has SF greater than the minimum acceptable. Analysis of the drawdown condition on effective stress results in SF less than acceptable (0.770 <1.2) for one section, but in terms of total stress the SF is adequate (1.459). Seismic analysis results in proper SF margin, and no permanent deformations are expected, according to the Newmark method because the peak ground acceleration is below the yielding acceleration (0.14g <0.295g).

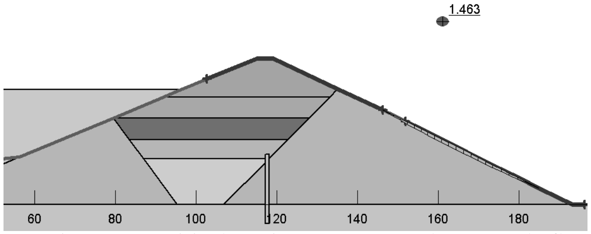

Figure 13. Critical section 3, Tenango dam. Steady flow condition, downstream failure. F.S =1.463 (Spencer´s method)

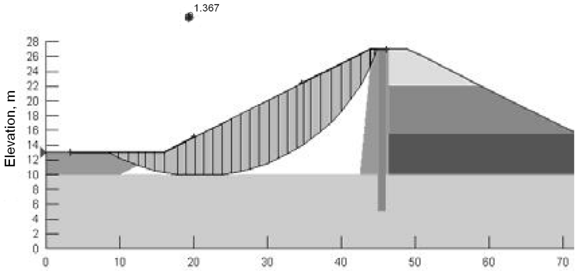

Figure 15. Critical section 3, La Laguna dam. Slip surface on upstream slope., rapid drawdown condition. F.S =1.367 (Spencer´method)

5 PHYSICAL-CHEMICAL BEHAVIOUR OF HYDRAULIC FILL

Chemical analyses of water from the reservoir and some springs (seepage pools) were performed to know the behavior of the clay and materials forming the dam and the minerals in the water reservoir. Water samples were analyzed for sodium, magnesium, calcium and sulfate content, total suspended solids and total solids, pH and alkalinity. To determine calcium, magnesium and sodium content atomic absorption spectrometry after chemical digestion based on the ASTM D 1971-02 was used.

These chemical analyses showed the susceptibility of the residual soils that form the embankment of the dam. It is important to know if to the clay presents dispersion or deflocculating because of its interaction with some of the minerals in the reservoir, mainly sulfates and those containing sodium and calcium ions.

In Tenango dam the sodium content in the reservoir is 4.4 mg/l, while in the springs their values are between 2.3 and 3.8. This allows us to determine that there is a low amount of sodium ions in the water that permeates through the embankment and therefore there is a possibility of reaction of clays with sodium ions retained. On the other hand the pH near 7 is a value that indicates that the clay at this acidity may have a dispersive behavior. A significant retention of sulfates is also observed.

In Necaxa Dam there is neither reaction nor deflocculating in the clay of the embankment, because the values of sodium content are virtually identical in reservoir water and water filtrations.

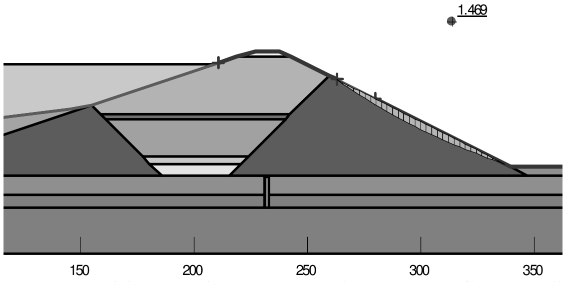

Figure 14. Critical section, Necaxa dam. Steady flow condition F.S = 1.69 (Spencer´s method)

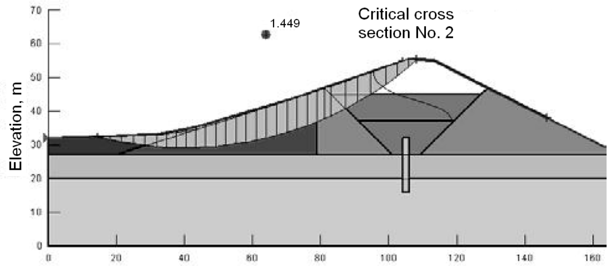

Figure 16. Critical section 2, Los Reyes dam. Rapid drawdown condition. F.S = 1.449 (Modified Bishop Method).

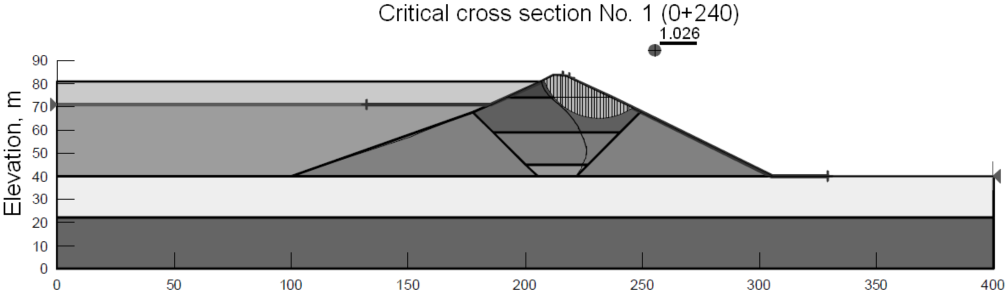

Figure 17. Critical section 1,Nexapa dam. Dynamic conditions. F.S = 1.026 (Spencer´s method)

The water reservoir samples of the Nexapa Dam have sodium content of 4.8 mg/l, calcium values of 24 mg/l. On the other hand, the water has high alkalinity with a pH of 8.76. So the reaction that might exist with the embankment clay would not be of dispersive type. So the piping phenomenon is not likely to occur.

The samples obtained in the reservoir of La Laguna dam have sodium content of 5.5 mg/l, calcium values of 7.5 mg/l, while in the springs the sodium content falls to 5.0 mg/l, calcium increases to 9.2 mg/l. The measured pH was between 6 and 6.85. So the reaction that might exist with the embankment clay would not be of dispersive type. So the piping phenomenon is not likely to occur.

The reservoir water samples obtained in Los Reyes Dam have sodium content of 5.3 mg/l, calcium values of 5.1 mg/l, while in the springs values decrease to 2.6 mg/l and 2.3 mg/l respectively. On the other hand, the water pH was between 6 and 7. So the reaction that might exist with the embankment clay would not be of dispersive type. So the piping phenomenon is not likely to occur.

However, it is important to periodically perform chemical analysis of water reservoir and springs to detect situations that might endanger the stability of dams.

6 CONCLUSIONS

In general, the dams of Necaxa Hydroelectric System (NHS) have sufficient stability conditions for the three analyzed conditions: steady-state flow, rapid drawdown and earthquake.

However, in Nexapa Dam, one of the critical sections has values somewhat lower than recommended. In this section the failures for steady-state flow, rapid drawdown and seismic excitation occur at the base of materials of brown silty clay with undrained strength of 21.5 and 35.75 kPa. It was mentioned above, that the resistance obtained with SPT tests corresponds to a material with hard consistency. So it is recommended to obtain undisturbed samples in these materials, to assess the stability of this dam in a more reliably way.

The Tenango dam does not have stability problems due to the strength characteristics of materials. However, during the drilling of some boreholes, large quantities of drilling mud were completely lost trough pipings of unknown dimensions and trajectories, which suggests that slip surfaces could be developed to continue the path of the pipings and the safety factors could be considered as intolerable. Moreover, the results of chemical analysis of water from the reservoir and spring revealed that the into the curtain of Tenango dam reactions may occur between clay and sodium ions and generate a dispersive behavior, so there probably is a piping phenomenon under way as might be confirmed by the loss of drilling mud described above. Based on the results here reported LyFC carried out the construction of plastic walls of bentonite-cement to reinforce those areas.

In Necaxa and Los Reyes dams the analyses indicate that there is not stability problems in the curtains and that tolerable distortion would arise if an earthquake occurs similar to that used in the design.

The stability analysis of La Laguna dam showed safety factors above the minimum acceptable in the three conditions of analysis. The chemical analysis of water from La Laguna dam showed no conditions for the development of piping but, because this phenomenon already occurred long ago, it is advisable to install instrumentation in the dam to observe changes in behavior that could indicate in time the possible development of a fault.

Finally, it is recommended to install instruments in the curtains of all dams in order to timely detect possible movements of the body and to monitor the structural and physical-chemical behavior of clay materials. This can be achieved through the implementation of fixed points for reference, inclinometers and piezometers.

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